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November 2001

Influences of Clearcut Harvesting and Fertilization on Structure and Function of the Soil Food Web in ICH Forests of Southern Interior British Columbia

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Abstract

This Extension Note describes some effects of clearcut harvesting and broadcast NPS fertilization on nitrogen (N) mineralization and components of the soil food web at three sites in the ICHmw subzone. We found that the forest floor in clearcuts had lower fungal hyphal lengths, total microbial biomass, microbial biomass N, and potential N mineralization than the forest floor in adjacent forests. Population densities of fungivorous, ominvorous, and predacious nematodes were reduced, and the ratio of bacterivorous/fungivorous nematodes was increased in the clearcuts. Nitrogen mineralization was correlated with bacterivorous and fungivorous nematodes in forest soils but not clearcut soils, suggesting that grazing by microbivorous nematodes may contribute to regulation of N mineralization in forests, and reduced grazing in clearcuts may account for the reduced N mineralization.
The effects of fertilization were more pronounced. We found that fertilization resulted in higher N mineralization and nitrate leaching, but had no effect on the amount of N sequestered in the microbial biomass, suggesting high potential for N losses to leaching and denitrification before seedlings are large enough to fully utilize the mineralizable N. Fertilization also resulted in an increased ratio of bacterial/fungal biomass and increased populations of bacterivorous nematodes, which together suggest that greater N mineralization was the result of increased bacterial turnover via nematode grazing. These results suggest that clearcut harvesting has the potential to reduce N availability in the short-term, but recovery may be hastened through forest floor and plant retention. In addition, broadcast fertilization at the time of planting can result in high N losses, but these losses may be minimized by delaying application until sites are fully occupied, and/or by applying fertilizer locally near individual seedlings.

Introduction

Most tree species require nitrogen (N) more than any other nutrient for their survival and growth. Nitrogen is an essential component of protein, and proteins (as enzymes) regulate all physiological activities, including photosynthesis. Nitrogen is made available for plant growth by the microbial decomposition of organic matter and the release of N contained

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106-06626/

in it, a process known as N mineralization. The organisms involved in N mineralization are influenced by silvicultural practices. For example, harvesting, broadcast burning, or fertilization may enhance N availability in the short term, whereas other silviculture practices, such as scalping of the forest floor or whole-tree harvesting, may have negative long-term effects. Fertilization at time of planting is practiced as a technique to enhance early seedling performance and possibly increase yields over the longer term. Mineral N applied as fertilizer to coniferous forest soils is incoporated rapidly, often within one growing season, into the microbial biomass and soil organic matter, a process known as N immobilization. After added mineral N has been immobilized and/or leached from the root zone, the availability of N for tree uptake and additional leaching depends on N mineralization.

Nitrogen in forest soils is cycled between various forms through the actions of both the soil biota (e.g., bacteria, fungi, nematodes, microarthropods) and abiotic factors (e.g., binding to soil particles, leaching) (Figure 1). Natural N inputs to the soil are deposition of animal wastes

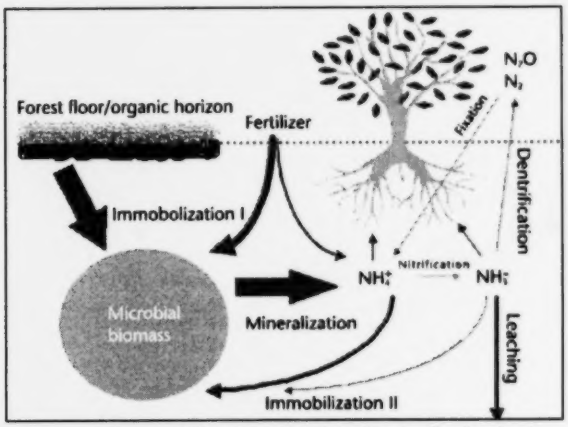
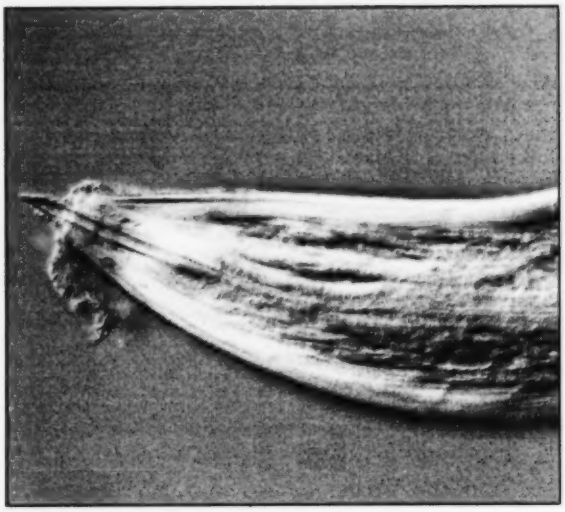


FIGURE 1 *Diagram of the nitrogen cycle in forest soils, showing inputs (including fertilizer), conversions, and losses of N. Biologically mediated processes are represented by arrows.*



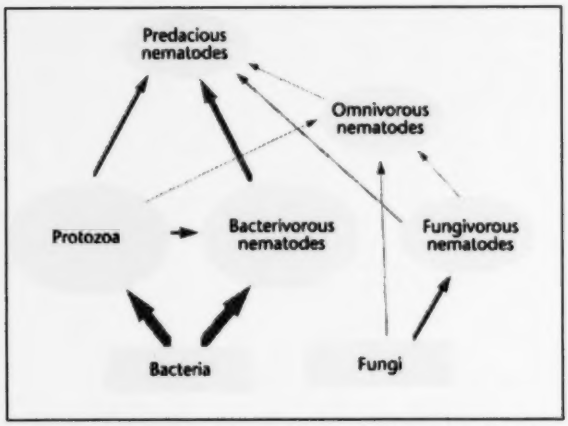


FIGURE 2 *Components of the soil food web evaluated in this study. Arrows indicate basic pathways of consumption. As protozoa and nematodes graze on bacteria and fungi, they consume nitrogen in excess of their metabolic requirements. The excess N is excreted as ammonium. Microarthropods are also important consumers of bacteria and fungi but were not considered in this study.*

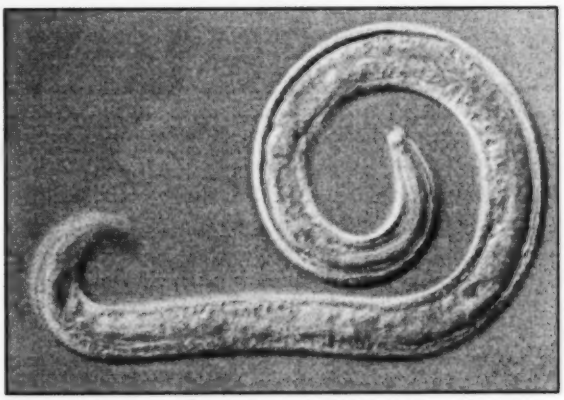


FIGURE 3 *Two examples of soil nematodes. Top:* Aporcelaimellus, *a predacious nematode. Note the spear-like mouthpart used for feeding. Bottom:* Chiloplacus, *a bacterivorous nematode.*

and plant debris, nitric acid (HNO_3) in precipitation, and biological fixation of N_2 gas in the air by soil- and plant-associated microorganisms (e.g., free-living *Azotobacter*, alder-associated *Frankia*, legume-associated *Rhizobium*). Nitrogen is made available for plant growth through decomposition of organic matter, incorporation of N into microbial biomass (bacteria and fungi), and subsequent mineralization of the microbial N as the microbial biomass is consumed by the soil micro- and meso-fauna (nematodes, protozoa, and microarthropods). These organisms form the core of the soil food web (Figure 2). Nematodes and protozoa usually represent less than 10% of the total soil biomass, but are particularly important contributors to microbial turnover and N mineralization (Figures 2 and 3). As bacteria and fungi degrade organic matter, they incorporate N into their biomass (Figure 1). As the micro- and meso-fauna consume bacteria and fungal cytoplasm, they excrete excess N as ammonium (NH_4^+). Excretion by protozoa and nematodes generally accounts for 25–40% of total N mineralization. Ammonium is then adsorbed to soil particles, taken up again by soil organisms (immobilizaition) or plants, lost to the atmosphere (volatilization), or converted by a few specific groups of bacteria to nitrite (NO_2^-) and then to nitrate (NO_3^-) (nitrification). The conversion of N in organic matter into inorganic mineral forms (NH_4^+ and NO_3^-), which are available for plant uptake, is collectively called N mineralization. Nitrate is subject to leaching loss in soil water, conversion by bacteria to N_2 gas (denitrification), re-immobilization by soil microorganisms, or uptake by plants.

Clearcutting and fertilization effects on N availability occur through changes in the activity and/or composition of the soil food web. However, we need to understand more about the nature or magnitude of these changes, whether they are positive or negative in the short and long term, and whether the soil ecosystem is resilient to the disturbances or inputs. In this study, we examined the effects of clearcut harvesting and fertilization on components of the N cycle and soil food web in Interior Cedar–Hemlock (ICH) forests. We undertook two separate studies using the same plots and analytical techniques. In the first study we evaluated the effects of clearcutting on N mineralization and nitrification, microbial biomass and abundance of microfauna, and relationships between biotic variables and N mineralization. In the second study, we evaluated the effects of broadcast fertilization (ammonium sulphate and ammonium phosphate) of clearcuts on the same variables. Fertilizers were broadcast applied in an attempt to reflect historically common practice in fast-growing broadleaf plantations, but this approach contrasts with most conifer plantations, where slow-release fertilizers are usually applied in smaller quantities near seedlings or in planting holes.

This Extension Note is intended for foresters and managers interested in the potential effects of fertilization and clearcutting on soil ecosystem processes in ICH forests. It may also be of interest to researchers interested in links between N cycling and the composition of the soil biota, forest certifiers interested in sustainability indicators for forest practices, and the general public interested in the biology of ICH forests. For further background information on the N cycle, readers are referred to Paul and Clark (1989). The information gained in this study should be helpful for management of wet-belt forests in a manner that sustains both soil and forest productivity.

Materials and Methods

Plot layout and sampling

Plots for both studies were established in 1996 in three geographically distinct areas within the ICH zone of the southern interior of British Columbia (Table 1). For the forest/clearcut comparison study, two clearcuts of similar age were located within each of the three areas described in Table 1. In October 1997 and June 1998, two 30 × 30 m plots were sampled in each of the six clearcuts as well as in six adjacent forested areas. In October 1996 and 1998, three such plots were sampled in each of the three clearcuts and adjacent forests (one of the clearcut/forest pairings in each of the three principal areas). Each soil sample was composed of soil from thirty 2.5 cm diameter × 10 cm deep cores. As cores were collected, the forest floor (L, F, and H horizons) and mineral soil (Ae or Ah, and Bh or Bm horizons) were separated. Data presented in this Extension Note are limited to the forest floor because biological activity and N mineralization were found to be more concentrated in forest floor than in mineral soil (Forge and Simard 2000). However, it should be noted that the mineral soil may contribute more than the organic horizon to the total biological activity and N mineralization of a site, largely due to the greater mass of mineral soil.

For the fertilization study, six plots were established within each of three clearcut sites (one clearcut was located in each of the three principal areas described in Table 1). At each site, two of the six plots were either left untreated (controls), or were fertilized with one of two fertilizer combinations:

1) Ammonium sulphate at 200 kg N/ha and 230 kg S/ha (NS);
2) Ammonium phosphate combined with ammonium sulphate

TABLE 1 *Vegetation and soil characteristics of the three principal experimental sites, prior to application of fertilizer treatments*

	Adams Lake	Chum Lake	Hidden Lake
Clearcut age in 1996 (years)	8	1	0
Biogeoclimatic unit	ICHmw3	ICHmw2	ICHmw2
Site series	04	01	01
Soil moisture	submesic	mesic	mesic
Soil nutrients	medium	medium	medium
Dominant tree species	*Pseudotsuga menziesii* *Betula papyrifera* *Thuja plicata* *Pinus monticola*	*Pseudotsuga menziesii* *Betula papyrifera* *Thuja plicata*	*Thuja plicata* *Betula papyrifera* *Pseudotsuga menziesii* *Larix occidentalis*
Soil classification	Humo-Ferric Podzol	Eutric Brunisol	Eluviated Eutric Brunisol
Forest floor	Mor (4 cm deep)	Moder (2.5 cm deep)	Mor (3 cm deep)
Soil texture	fine loamy sand	sandy loam	sandy loam
Elevation (m)	460	580	520
Drainage	well	well	moderately well
Latitude	51°13'20"	50°49'00"	50°34'00"
Longitude	119°31'30"	119°35'00"	118°49'00"
Annual precipitation (cm)	90	51	70
Average temperature (°C)	7.5	8.0	7.8

(5.6:1 mixture), resulting in 200 kg N/ha, 200 kg P/ha, and 182 kg S/ha (NPS).

The two untreated plots in each clearcut were the same as those used in the clearcut/forest comparison study. The fertilizers were broadcast-applied by hand between June 13 and 15, 1997, at all three sites. Four weeks prior to fertilization, one of the two plots of each fertilizer treatment and control at each site was planted with paper birch (*Betula papyrifera*) seedlings and the other plot was planted with black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) seedlings. Three lysimeters were installed at 30 cm depth in each plot to collect soil leachates (soil water containing dissolved nutrients) from the overlying forest floor, A and B horizons. The leachates were recovered at approximately monthly intervals during the growing seasons of 1997 and 1998, and analyzed for nitrate concentration.

Soil analyses

Each soil sample was analyzed for N mineralization, populations of soil organisms, and soil chemical properties. The assays are described briefly below. More detailed descriptions of the procedures have been published (Forge and Simard 2000, 2001a, 2001b).

We used two different tests of N availability. The first test involved aerobic incubation of the samples to measure potential of the soil to release N (potential N mineralization). In the second test, samples were incubated anaerobically for 14 days. Anaerobic incubation has been used as a general indicator of N availability in forest soils. More recently, anaerobically mineralized N has been found to represent microbial N.

Total bacterial abundance and fungal hyphal lengths were measured using microscopic methods. Bacterial numbers and hyphal lengths were converted to total microbial biomass using mean cell sizes (measured) and recorded specific densities. Most Probable Number (MPN) procedures were used for enumerating protozoa and denitrifying bacteria. Nematodes were extracted from 50-g subsamples of soil using a Baermann pan technique. A subsample of the nematodes extracted were identified to genus, and categorized into bacterivorous, fungivorous, omnivorous, and predacious feeding groups (feeding on bacteria, fungi, mixed diet, and microfauna, respectively). Microarthropods were not addressed in this study.

A portion of each soil sample was air-dried at room temperature and analyzed for pH, total carbon (C), total N, extractable phosphorus (P), extractable sulphate, and exchangeable cations (Al, Ca, K, Mg, Mn, and Na) by the British Columbia Ministry of Forests Research Branch Laboratory, Victoria, B.C.

Results and Discussion

Forest/clearcut study

Clearcuts had significantly lower hyphal biomass, total microbial biomass, microbial N (anaerobic incubation), and potential N mineralization (aerobic incubation) than adjacent forests (Table 2). The most conspicuous effects of clearcut harvesting on structure of the nematode community were significantly reduced population densities of fungivorous, omnivorous, and predacious

nematodes, and an increased ratio of bacterivorous/fungivorous nematodes (Table 2). The reduced biomass of fungal hyphae, and associated reduced abundance of nematodes, in soil of clearcuts were undoubtedly the result of reduced inputs of organic matter to the soil via tree roots, ectomycorrhizae, and litterfall. It is not clear if the reduced biomass of fungal hyphae and nematodes represents a potentially long-term negative effect on the soil food web and the functions it performs. Alternatively, the soil food web may be resilient and the biomass of fungal hyphae and nematodes may increase with the eventual re-establishment of trees and increased inputs of organic matter. The reduced microbial biomass does, however, indicate reduced capacity for microbial immobilization of ammonium and nitrate and, therefore, increased potential for losses to leaching and denitrification.

There were positive correlations between the abundances of fungivorous and bacterivorous nematodes and N mineralization in forest soils (Table 2). We speculate that grazing by fungivorous nematodes may be an important component of N mineralization in forest soils, and reduced grazing by fungivorous nematodes may be an important factor contributing to the reduced N mineralization in clearcuts. These correlations have led us to consider using microbivorous nematodes as indicators of N availability in evaluation of management impacts on soil ecosystems and for site characterization. Our results contrast with some previous studies showing increased N mineralization 5–10 years following clear-cutting, commonly attributed to increased organic matter decomposition (Paul and Clark 1989), probably because our clearcuts contained lower quantities of appropriate-quality logging residues and slower rates of re-vegetation.

Short-term responses to fertilization

The potential benefits of fertilization must be evaluated against the potential for N losses to leaching, runoff, and denitrification, and potential changes to the soil ecosystem. As expected, the cottonwood and birch seedlings in fertilized plots were larger after 1 year's growth than in control plots (data not shown). Fertilizer-enhanced growth in the short term may not necessarily result in significant differences in growth in later years, especially if considerable amounts of N are lost to leaching and denitrification. Consequently, it is premature to discuss the benefits of fertilization to tree growth in this study.

Previous studies have demonstrated significant immobilization of fertilizer N into microbial biomass and organic matter of forest soils within one growing season. We found that anaerobically mineralized N, a

TABLE 2 *Effects of clearcut harvesting on N mineralized during aerobic and anaerobic incubations, fungal hyphae, bacteria, microbial biomass, and bacterivorous, fungivorous, omnivorous, and predacious nematodes, and coefficients of correlations between nematode variables and N mineralization*

		N mineralized (Aerobic)	N mineralized (Anaerobic)	Hyphae	Bacteria	Microbial biomass	Nematodes (per 100 g soil)†				
		(mg N kg^{-1})	(mg N kg^{-1})	(mg^{-1})	(log cells g^{-1})	(mg g^{-1})	Bact	Fung	B/F	Omni	Pred
1996 (n=3)	Clearcut	ND‡	ND	923*	9.33*	2.76*	4866	3682*	1.20*	165*	356*
	forest	ND	ND	1602	9.63	4.45	5658	7764	0.75	530	1464
1997 (n=6)	Clearcut	4.3	129.5	1363*	9.75	4.43*	4066	3169*	1.36*	251	412*
	forest	1.4	186.1	2204	9.84	6.53	3853	6569	0.58	273	537
1998 June (n=6)	Clearcut	11.2*	70.7*	ND	ND	ND	1093	730*	1.71*	39*	95*
	forest	45.2	141.7	ND	ND	ND	934	1310	0.78	89	234
1998 October (n=3)	Clearcut	8.6	ND	ND	ND	ND	1076	956*	1.42*	101	173*
	forest	14.5	ND	ND	ND	ND	1160	2675	0.64	55	255
Coefficients of correlation with N mineralization	Clearcut	ND	ND	ND	ND	ND	0.50	0.52	-0.26	0.46	-0.65§
	forest	ND	ND	ND	ND	ND	0.74§	0.83§	0.02	0.51	0.16

† Nematode groups: Bact = bacterivorous, Fung = fungivorous, Omni = omnivorous, Pred=predacious, B/F = ratio of bacterivorous/fungivorous nematodes.

‡ Not determined.

* Value for clearcut is significantly different from value for forest ($P < 0.05$).

§ Significant correlation ($P < 0.05$).

measure of microbial N, was not increased by fertilization of the clearcuts (Table 3). This suggests that the microbial biomass did not take up (immobilize) significant amounts of applied N in our study. This lack of microbial immobilization of N likely contributed to the losses to leaching. We observed significantly greater leaching of nitrate from fertilized soil than from nonfertilized soil in clearcuts during the first year after fertilizer application (Table 4). The abundance of denitrifying bacteria was also greater in fertilized soil than in nonfertilized soil 16 months after fertilization (Table 3), indicating that potential N losses to denitrification were also greater in fertilized soil. Potential N mineralization (aerobic incubation) was six times greater in fertilized soil than in nonfertilized soil at the fall sampling dates 4 and 16 months after fertilization, but not at the spring sampling date 12 months after fertilization (Table 3). The high rates of N mineralization and nitrification (data not shown) and lack of retention of N by the microbial biomass in fertilized soil up to 16 months after fertilization indicate that considerable amounts of N could be lost to leaching and denitrification before seedlings are large enough to fully utilize the mineralized N.

We were unable to detect significant changes in total microbial biomass following fertilization (Table 3) and it is likely that fertilizer-induced increases in N mineralization were brought about by changes in structure of the soil food web rather than changes in size of the microbial biomass. We observed an increase in the ratio of bacterial biomass/fungal biomass, increased populations of bacterivorous nematodes, and an increased ratio of bacterivorous/fungivorous nematodes (Table 3). Increased populations of bacterivorous nematodes indicate increased bacterial production and turnover even when standing crop microbial biomass remains unchanged. Changes in the soil ecosystem resulting in greater bacterial production, and turnover via grazing by bacterivorous microfauna, will result in greater N mineralization. The increased production and turnover of bacteria, relative to that of fungi, could have been the result of greater inputs of litter and root exudates from the plant community, which was considerably more lush in fertilized plots. The regenerating plant community was dominated by wild currant (*Ribes* spp.) and wild rose (*Rosa* spp.) at Adams Lake, Canadian thistle (*Cirsium arvense*), wild rose, and birch-leaved spirea (*Spiraea betulifolia*) at Chum Lake, and Canadian thistle and wild raspberry (*Rubus* spp.) at Hidden Lake.

The ratios of bacterial biomass/fungal biomass and bacterivorous nematodes/fungivorous nematodes both tended to be greater in the NPS treatment than in the NS treatment, but the effects

TABLE 3 *Effects of fertilization with ammonium sulphate (NS) or ammonium sulphate plus ammonium phosphate (NPS) on nitrogen mineralized during aerobic incubation, abundance of bacteria, hyphal lengths, and abundance of denitrifying bacteria and nematode feeding groups in October of 1997, June and October of 1998, and October of 1999*

Treatment	N mineralized (mg N kg^{-1})	Bacteria (log cells g^{-1})	Hyphae (mg^{-1})	B/F†	Denitrifiers (log cells g^{-1})	Nematodes (per 100 g soil)‡ Bact	Fung	B/F	Omni	Pred
October 1997										
Control	8.9	9.78	1559	0.84	ND§	4132	3048	1.39	234	446
NS	59.8*	9.77	1483	1.01	ND	4656	2596	1.82	218	175*
NPS	71.4*	9.70	1238	0.98	ND	4571	2985	2.01	211	315
June 1998										
Control	8.5	ND	ND	ND	4.94	1025	783	1.34	37	130
NS	7.1	ND	ND	ND	5.82	1601	803	2.60	52	118
NPS	11.1	ND	ND	ND	5.87	2008*	851	3.13*	45	162
October 1998										
Control	8.6	9.50	872	0.78	3.94	1076	956	1.42	101	173
NS	55.5*	9.53	801	0.94	5.40*	1879	740	2.97	71*	145
NPS	54.8*	9.58	718	1.23*	5.36*	2189*	629	3.55*	21*	171
October 1999										
Control	ND	9.45	1695	0.43	ND	2908	2710	1.49	250	414
NPS	ND	9.61*	1775	0.56	ND	10565*	2250	4.22*	204	535

† Ratio of bacterial biomass/fungal biomass.

‡ Nematode groups: Bact = bacterivorous, Fung = fungivorous, Omni = omnivorous, Pred = predacious, B/F = ratio of bacterivorous/fungivorous nematodes .

§ Not determined.

* Significantly different from the control ($P < 0.05$).

TABLE 4 *Nitrate concentrations (mg L^{-1}) in leachate collected from zero-tension lysimeters at four times after fertilizer application. Ammonium sulphate (NS) and ammonium sulphate plus ammonium phosphate (NPS) fertilizers were applied June 13–15, 1997*

	Collection period			
Treatment	July 15 – August 2, 1997	October 12 – November 1, 1997	May 16 – June 30, 1998	October 19 – November 16, 1998
Control	1.27	2.84	1.60	9.07
NS	46.34*	39.58*	5.12*	5.75
NPS	20.01	29.98*	4.78	5.29

* Significantly greater than the control ($P \leq 0.05$).

were not statistically significant (Table 3). Apparently, the soil food web is not affected strongly by increased P availability in these soils, perhaps because levels of extractable P were already relatively high (Forge and Simard 2001a).

Summary and Management Implications

Clearcutting reduced potential N mineralization, microbial biomass N, total microbial biomass, fungal biomass, abundance of fungivorous, omnivorous, and predacious nematodes, and increased the ratio of bacterivorous/fungivorous nematodes.

By reducing microbial biomass, clearcutting reduced the capacity for microbial immobilization of ammonium and nitrate, and therefore increased the potential for losses of N to leaching and denitrification.

Reduced biomass and activity (i.e., N mineralization) of soil organisms was likely the result of reduced inputs of organic matter to the soil. Well-known soil conservation techniques, such as retention of the forest floor and protection of the native plant community during silvicultural practices, would reduce the impact of clearcut harvesting and facilitate recovery along the successional pathway.

Fungivorous and bacterivorous nematodes are potential indicators of N availability, and therefore may be useful for site characterization, as indicators of sustainability, and to provide a focus for studies on management impacts on soil ecosystems.

Fertilization resulted in greater N mineralization, nitrate leaching, and populations of denitrifying bacteria, suggesting high potential for N losses from fertilized sites.

Losses of N would likely be minimized by delaying application until sites are fully occupied (e.g., at crown closure) and root and microbial biomasses are sufficient to immobilize the fertilizer and mineralized N. Where fertilizer is applied around the time of planting, however, N losses may be reduced by placing it in holes or small areas near seedlings (e.g., after Van den Driessche 1999), keeping in mind the unknown implications of these treatments for seedling growth and survival.

Long-term measurements are required to fully quantify the benefits of the fertilization treatments to forest productivity, and to determine whether the benefits outweigh the monetary costs of lost fertilizer and the environmental costs of nitrate leaching.

Further research is also required on the longer-term consequences of clearcutting- and fertilizer-induced changes in the soil biota and decomposition/mineralization pathways, the reversibility of such changes, and the implications for long-term soil productivity.

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Acknowledgements

The authors wish to thank Dr. Graeme Hope for advice on

experimental techniques and for reviewing an earlier draft of this Extension Note. Working plan reviews and study advice were also provided by Robert Brockley, Bill Chapman, and Kevin Brown. We are grateful to Shannon Berch, Robert Brockley, Kevin Brown, Tim Conlin, Marty Kranebetter, and Alan Vyse for reviewing the manuscript. We thank Barbara Zimonick and Trevor Blenner-Hassett for assistance with plot location, planting, sampling, and analyses. We appreciate the assistance of Jim Wright, Don Purdy, and Dan MacDonald in location of the study sites. Funding for this research and extension was provided by Forest Renewal BC. Funding assistance by Forest Renewal BC does not imply endorsement of any statements or information contained herein.

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